Outcomes of long bones treated with carbon-fiber nails for oncologic indications: international multi-institutional study

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Research Article

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J Am Acad Orthop Surg 2023;00:1-12

DOI: 10.5435/JAAOS-D-22-01159

ABSTRACT

Background: Intramedullary nail fixation is commonly used for prophylactic stabilization of impending and fixation of complete pathological fractures of the long bones. However, metallic artifacts complicate imaging evaluation for bone healing or tumor progression and postoperative radiation planning. Carbon-fiber implants have gained popularity as an alternative, given their radiolucency and superior axial bending. This study evaluates incidences of mechanical and nonmechanical complications.

Methods: Adult patients (age 18 years and older) treated with carbon-fiber nails for impending/complete pathological long bone fractures secondary to metastases from 2013 to 2020 were analyzed for incidences and risk factors of mechanical and nonmechanical complications. Mechanical complications included aseptic screw loosening and structural failures of host bone and carbon-fiber implants. Deep infection and tumor progression were considered nonmechanical. Other complications/adverse events were also reported.

Results: A total of 239 patients were included; 47% were male, and 53% were female, with a median age of 68 (IQR, 59 to 75) years. Most common secondary metastases were related to breast cancer (19%), lung cancer (19%), multiple myeloma (18%), and sarcoma (13%). In total, 17 of 30 patients with metastatic sarcoma received palliative intramedullary nail fixation for impending/complete pathological fractures, and 13 of 30 received prophylactic nail stabilization of bone radiated preoperatively to manage juxta-osseous soft-tissue sarcomas, where partial resection of the periosteum or bone was necessary for negative margin resection. 33 (14%) patients had complications. Mechanical failures included 4 (1.7%) structural host bone failures, 7 (2.9%) implant structural failures, and 1 (0.4%) aseptic loosening of distal locking screws. Nonmechanical failures included 8 (3.3%) peri-implant infections and 15 (6.3%) tumor progressions with implant contamination. The 90-day and 1-year mortalities were 28% (61/239) and 53% (53/102), respectively. The literature reported comparable failure and mortality rates with conventional titanium treatment.

Conclusions: Carbon-fiber implants might be an alternative for treating impending and sustained pathological fractures secondary to metastatic bone disease. The seemingly comparable complication profile warrants further cohort studies comparing carbon-fiber and titanium nail complications.

Intramedullary nail fixation has been a long-standing treatment of impending or complete pathologic fractures of the long bones secondary to metastatic bone disease.[1-6] With sustained increases in the lifespan of patients with cancer with metastatic disease, the treatment of neoplastic pathologic fractures is gaining more importance as preservation of motion and function continues to become more needed in this patient population.[1,6-9]

Recently, carbon-fiber (CF) has gained popularity as an alternative to conventional metal implants.[10,11] With higher biocompatibility (referring to the ability of the implant to not elicit a host response after implantation),[12] low weight-to-strength ratio, and increased bending strength when compared with titanium,[13] CF implants may be a more desirable treatment option for naturally unhealable pathologic fractures.[10,11,14] Additional benefits include CF's fatigue strength and closer modulus of elasticity to bone.[15-17] Its radiolucency and lack of scattering effect on MRI and CT are also appealing for imaging surveillance and theoretical treatment planning for postoperative radiation, as demonstrated in CF spinal implant studies (Figure 1).[11,14,18-20] Although relatively high nonunion rates were reported in a single center using 16 CF nails for diaphyseal correction osteotomy (11 limbs), shortening surgery (3 limbs), and diaphyseal closed tibia fractures (2 limbs), low nonunion rates were reported in a multicenter study with 96 oncologic patients treated with CF plates.[21,22]

As drawbacks, some argue that the lack of malleability makes using plates challenging in fracture care and question whether CF nails are more expensive than metal nails. However, costs are competitive with metal nails, and bending of CF nails is often not necessary during surgery.[23] Despite the previously mentioned benefits, the literature is limited regarding complications, pitfalls, and pearls of using CF nails in patients with metastatic cancer with osseous involvement. This study is an early experience of the "Carbon-Fiber International Collaboration Initiative" (CF-ICI) which includes 13 centers in Europe, the Middle East, the United Kingdom, and the United States, participating in an international, worldwide, prospective registry.

This study aims to assess implant complications categorized as structural and nonstructural with their respective predictors concerning the use of CF femoral, tibial, and humeral nails for the management of impending or complete pathologic fractures of long bones secondary to metastatic bone disease or sarcoma treatment.

Methods

Study Design and Setting

This is a multicenter, retrospective, international study approved by each of the 13 participating institutions'

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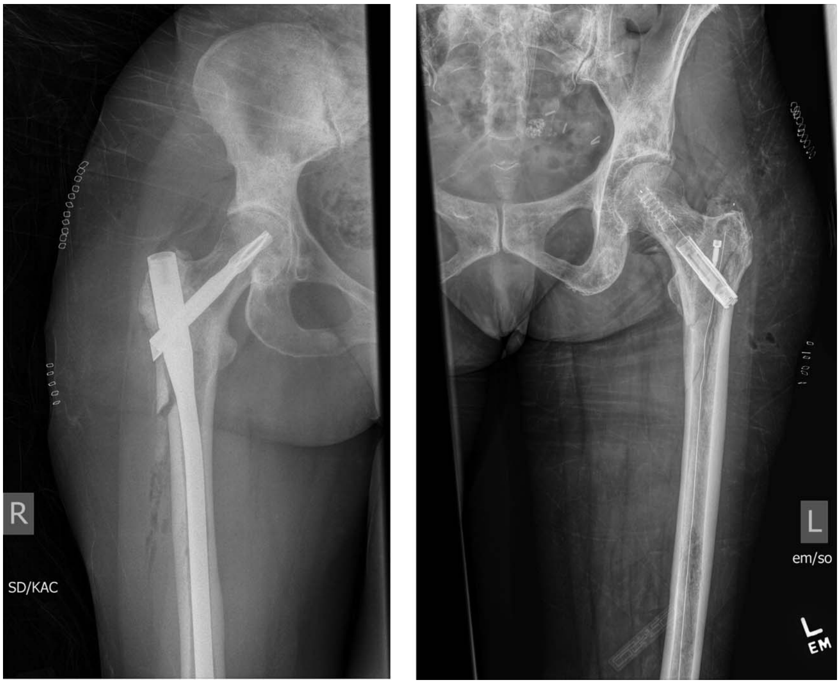
Supplemental digital content is available for this article. Direct URL citation appears in the printed text and is provided in the HTML and PDF versions of this article on the journal's Web site (www.jaaos.org).

Description: A multi-institutional study assessing the mechanical and nonmechanical complication rates of adult patients treated with carbon-fiber nails for impending/complete pathological long bone fractures secondary to metastases from 2013 to 2020.

Conflict of interest by the authors: Each author certifies that there are no funding or commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article related to the author or any immediate family members.

This study was approved by our institutional review board, has been performed in accordance with the ethical standards in the 1964 Declaration of Helsinki, and carried out in accordance with relevant regulations of the US Health Insurance Portability and Accountability Act (HIPAAA).

Figure 1



Radiograph showing a conventional titanium nail (left) and carbon-fiber nail (right) in the femur.

Institutional Review Boards. The data were collected from a prospective registry enrolling patients treated with CF implants. An online database created in Leiden (using Castor electronic data capture [EDC]) coordinated and hosted the prospective data registry for Europe, the Middle East, the United Kingdom, and the United States through data exchange agreements. This study adhered to the Strengthening Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[24] None of the participating institutions received funding to support research focusing on CF implants. Investigators who have received fees as consultants or paid speakers declared their conflicts based on publication guidelines.

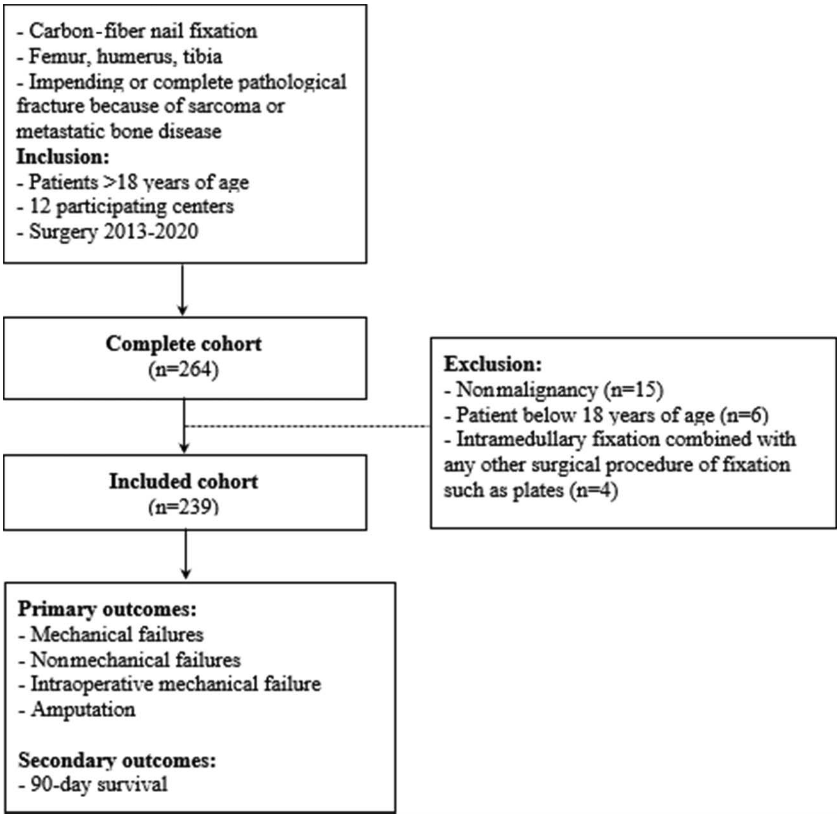
Participants/Study Subjects

Between 2013 and 2020, we included all adult patients (18 years or older) with impending or complete pathologic fractures to the long bones secondary to metastatic bone disease, with oligometastatic bone sarcoma or oligometastatic disease secondary to renal cell, breast, and papillary thyroid carcinoma who were treated with metastasectomy and reconstruction using a CF nail and with soft-tissue sarcomas treated with preoperative and/or postoperative radiation who required partial excision of bone or periosteum as part of the margin for oncologic treatment and were fixated prophylactically with a CF nail. Patients in the described groups were included in a registry that continues to prospectively include data to assess the long-term safety and effectiveness of CF implants. The choice of treatment was made by shared decision making between the patient and surgeon. In general, surgery was recommended for oncological patients with impending or actual pathological fractures, mechanical axial loading pain, and no response to radiation therapy or oral narcotic pain medication. The operating surgeon chose to use a CF plate instead of a megaprosthesis. Factors in the decision included tumor location and amount and quality of remaining bone available for intramedullary nail fixation. Exclusion criteria included[1] patients younger than 18 years,[2] surgery due to nonmalignancy,[3] and intramedullary fixation combined with any other surgical procedure of fixation, such as plates (Figures 2 and 3).

Description of Surgery

The choice of treatment was decided by mutual agreement between the patient and surgeon. The operating surgeon chose to use a CF nail. All patients with humeral lesions received the CarboFix long humeral nail, which is noncannulated and 8.5 mm in diameter and has a locking mechanism consisting of two 4.5 mm proximal screws and up to three distal 3.5 mm screws. All patients with femoral lesions received the CarboFix long femoral nail with a trochanteric entry, which is cannulated and 11 to 12 mm

Figure 2



Flow diagram illustrating patient selection and outcome measures.

in diameter and has a securing mechanism consisting of a 10.4 mm lag screw size 80 to 110 mm secured with a set screw and two distal femoral 4.0 mm screws. All patients treated with tibial nails received the CarboFix tibial nail, which is cannulated and 10 to 11 mm in diameter and has a securing mechanism consisting of two proximal 5.0 mm screws, one 4.0 mm dynamic proximal screw, and three 4.0 mm distal locking screws. Most patients had two screws for distal fixation. Lateral or supine patient positioning varied depending on the surgeon's experience and preference. In general, surgery was recommended for patients with mechanical, axial-loading pain in the affected extremity, with no response to radiation therapy, or with high, oral-narcotic pain medication use. Patients with complete fractures were treated independently of previous symptomatology. At the 2-week, 6-week, 3-month, 6-month, and 1-year postoperative follow-ups, patients received clinical and radiographic evaluations (pending oncologic status). Patients were cleared for radiation therapy and/or chemotherapy 7 to 10 days after the surgical procedure. All patients were made weight bearing as tolerated after surgery.

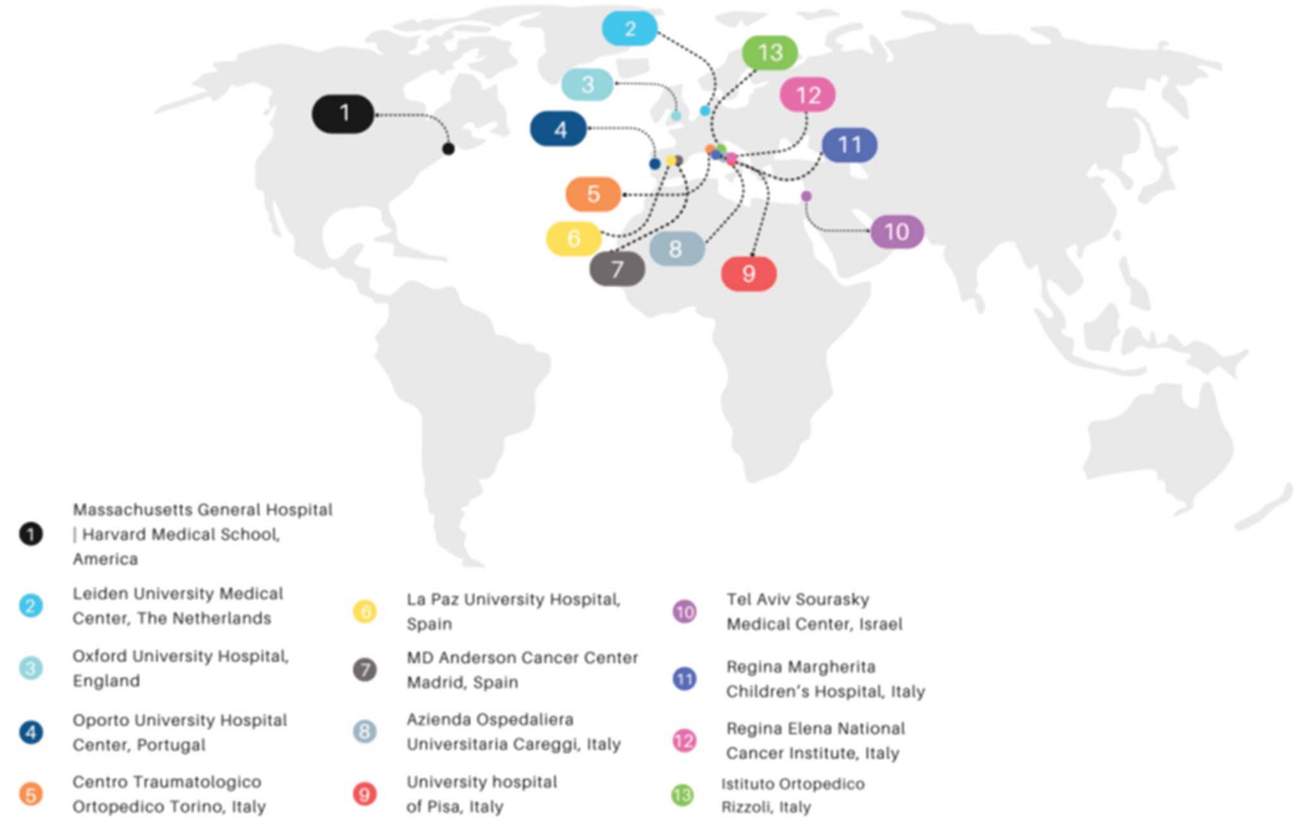
Description of Radiation Therapy

The exact doses were not collected in this study because of protocol variation between institutions. Radiation oncology treatment was also not the focus of our investigation. Nevertheless, in general, patients with metastatic bone disease were treated with either 400 centigray (cGy) divided into 5 fractions or 300 cGy divided into 10 fractions. In patients treated for soft-tissue sarcomas, the radiation dose was 5,000 to 5,400 cGy divided into 25 fractions if delivered preoperatively or 6,000 cGy divided into 30 fractions if delivered postoperatively. Preoperative radiation patients who required a postoperative radiation boost, received a single dose between 1,200 to 1,600 cGy depending on preoperative radiation dose and tumor histology.

Outcome Measures and Explanatory Variables

The primary outcome was measured by postoperative complications cataloged as mechanical or nonmechanical. Mechanical complications included[1] aseptic screw loosening,[2] structural failure of the host bone, such as peri-implant fractures or hip screw cutout,[3] and structural failures of the

Figure 3



World map depicting all 13 participating institutions.

CF implant per se such as primary fracture of the implant or secondary to fracture nonunion or tumor progression. Nonmechanical complications included[4] deep infections requiring surgical treatment[5] and tumor progression without structural failure of the implant. Tumor progression causing implant failure, such as nail breakage, was counted as both, nonstructural failure (tumor progression) and structural failure, given that the implant ultimately broke. Complications related to implant use, such as superficial wound dehiscence, superficial wound infection, thromboembolic events, perioperative adverse events, and implant use–related deaths were also reported. The secondary outcome measures were 90-day and 1-year mortality by any cause after surgery.

The following clinical factors were obtained: age; sex; smoking status; American Society of Anesthesiologists (ASA) score; primary tumor type, prognosis (as classified by Katagiri, et al[25]), and grade; additional bone metastases to surgical site; preoperative chemotherapy and/or radiation therapy; postoperative chemotherapy and/or radiation therapy within 3 months of surgery; pathological fracture; surgical site; location of bone; use of cement; allograft or autograft; surgical margin; and implant type.

Accounting for all Patients

Of the 264 patients with CF nails, 9.5% (20/264) were excluded because of nonmalignancy (n = 15), younger than 18 years (n = 6), and another implant concomitantly used (n = 4). The remaining 239 patients were included. Loss to follow-up was 8.8% (21/239) at 90 days and 19% (45/239) at 1 year. Missing patients were at random. The median follow-up time was 17 months (IQR, 4 to 49). Follow-up was verified until June 1, 2021.

Statistical Analysis

Variables are presented as frequencies (percentages for categorical variables) and medians (IQRs for continuous variables because they were not normally distributed based on histogram inspection).

No comparative analyses were performed between the complication profile in our study cohort and from the literature given the heterogeneity in the conventional titanium nail literature of study populations, selection criteria, and outcomes. Bivariate logistic regression was used to assess explanatory variables associated with four groupings of mechanical and nonmechanical complications[1]: overall complications without time constraint,[2] overall

Table 1. **Characteristics of Patients Treated Surgically With Carbon-Fiber Nails for Impending or Pathological Fracture (n = 239)**

Variables	% (n)
Age (yr), median (IQR)	68 (59-75)
Male	47 (113)
Smoking[a]	26 (51)
ASA score[a]	
1-2	25 (56)
3-4	75 (166)
Underlying disease	—
Metastatic carcinoma	87 (209)
Soft-tissue sarcoma	13 (30)
Primary tumor group	
Good prognosis[b]	38 (90)
Poor prognosis	62 (149)
Tumor grade	
Low	14 (33)
High	86 (206)
Additional bone metastases to surgery site	82 (197)
Preoperative chemotherapy[a]	61 (134)
Preoperative radiation therapy to surgery site[a]	14 (30)
Postoperative chemotherapy[a]	52 (103)
Postoperative radiation therapy[a]	45 (99)
Surgical variables	
Surgical side	
Left	52 (125)
Right	48 (114)
Pathological fracture	49 (116)
Location of surgery	
Femur	55 (132)
Humerus	36 (87)
Tibia	8.4 (20)
Location of bone	
Diaphyseal	66 (157)
Metadiaphyseal	28 (68)
Combined	5.9 (14)
Cement[c]	11 (27)
Allograft[d]	0.4 (1)
Autograft[d]	0.4 (1)
Surgical margin	
Intralesional	65 (156)
Marginal[e]	2.5 (6)
Wide	6.7 (16)
No resection	26 (61)
Primary total knee prosthesis[f]	0.8 (2)

(*continued* in next column)

Table 1. (*continued*)

IQR = interquartile range, ASA = American Society of Anesthesiologists
[a]Missing data were present in smoking for 16% (39/239); nonsmoker was defined as stopped at least 6 months before surgery; ASA score in 7.1% (17/329); preoperative chemotherapy in 7.9% (19/239); preoperative radiation therapy in 7.9% (19/239); postoperative chemotherapy in 18% (42/239); and postoperative radiation therapy in 8.8% (21/239).
[b]Good prognosis group includes patients with lymphoma, multiple myeloma, breast cancer, kidney cancer, prostate cancer, or thyroid cancer. Poor prognosis includes patients with lung cancer, colon cancer, rectal cancer, bladder cancer, esophageal cancer, liver cancer, melanoma, gastric cancer, or other cancers.
[c]All 11 patients had metastatic disease.
[d]Both patients had soft-tissue sarcomas.
[e]Marginal surgical margin occurred in five patients with soft-tissue sarcoma and one patient with renal metastases.
[f]Two patients had a primary total knee arthroplasty before they received a femoral carbon-fiber nail in the same leg.

complications within 1-year of surgery,[3] complications without nonstructural type tumor progression and no time constraint, and[4] complications without nonstructural type tumor progression within 1 year. The results were presented as odds ratios (OR) with 95% confidence intervals. Multiple chained imputation (n = 40) was used to estimate missing values for smoking in 39 patients (16%), ASA scores in 17 patients (7.1%), preoperative chemotherapy in 19 patients (7.9%), preoperative radiation therapy at surgery site in 19 patients (7.9%), postoperative chemotherapy in 42 patients (18%), and postoperative radiation therapy in 21 patients (8.8%). Of the 239 patients, 132 patients (55%) had a date of death. Of the remaining 107 patients (44%), the median follow-up time was 424 days (IQR, 142 to 894 days). A two-tailed *P*-value of < 0.05 was considered significant. Bonferroni correction was used for multiple comparisons. All statistical analyses were performed using Stata 15.0 (StataCorp LP).

Results

Study Population

This study included 239 patients: 47% were male and 53% were female, with a median age of 68 (IQR, 59 to

Table 2. Characteristics of Tumors (n = 239)

Tumor grade	% (n)
Breast	19 (46)
Lung	19 (45)
Multiple myeloma	18 (42)
Soft-tissue sarcoma	13 (30)
Kidney	7.5 (18)
Others	7.1 (17)
Colorectal	2.9 (7)
Prostate	2.5 (6)
Liver	2.5 (6)
Endometrium	2.5 (6)
Thyroid	1.7 (4)
Melanoma	1.3 (3)
Lymphoma	1.3 (3)
Ovarian	0.4 (1)
Oropharyngeal	0.4 (1)
Gastric	0.4 (1)
Urothelial	0.4 (1)
Unknown	0.8 (2)

75; Table 1) years. Most patients had an ASA score of 3 to 4 (75%). The most common primary tumors included those related to breast cancer (19%), lung cancer (19%), multiple myeloma (18%), and sarcoma (13%; Table 2). Of the 239 surgical margins, 65% were intralesional, 6.7% wide, 2.5% marginal, and 26% had no resection. The location of surgery included the femur (55%), humerus (36%), and tibia (8.4%). The 90-day mortality was 28% (61/239), and 1-year mortality was 53% (53/102) which is comparable with patients treated with conventional titanium nails in the literature[26] (Supplementary Tables 1, http://links.lww.com/JAAOS/A953, and Table 3, http://links.lww.com/JAAOS/A955).

Complications

In total, 33 patients (14%) had structural and nonstructural events defined as complications, of which 22 (9.2%) occurred within 1 year. Mechanical failures included 1 (0.4%) with aseptic loosening of the distal locking screws within 2 years (1 femoral nail), 4 (1.7%) with host bone structural failures, and 7 (2.9%) with implant structural failures (5 femoral nails and two humeral nails) (Figure 4). One of the humeral nail failures occurred in a patient who required an intercalary resection because of a synovial sarcoma single bone metastasis and reconstruction with a cement spacer

Table 3. Outcomes of Patients Treated Surgically With Carbon-Fiber Nails for Impending or Pathological Fracture (n = 239)

Outcome	% (n)
Mechanical failures	5.0 (12)
Aseptic loosening of the implant screws	0.4 (1)
Structural failures of the host bone peri-implant fractures, hip screw out	1.7 (4)
Structural failures of the carbon-fiber implant	2.9 (7)
Femur	2.1 (5)
Humerus	0.8 (2)
Nonmechanical failures	9.2 (22)
Deep infections requiring surgical treatment	3.3 (8)
Tumor progression	6.3 (15)
Mortality[a]	
90 d	28 (61)
1 yr	53 (102)
Intraoperative mechanical failure	1.3 (3)
Amputation	0.8 (2)
Soft-tissue failure because of aseptic wound dehiscence	0.8 (2)

[a]Loss to follow-up was 8.8% (21/239) for 90-day mortality, 13% (31/239) for 180-day mortality, and 19% (45/239) for 1-year mortality. The median follow-up time was 199 days (interquartile range: 53-588 days).

Figure 4

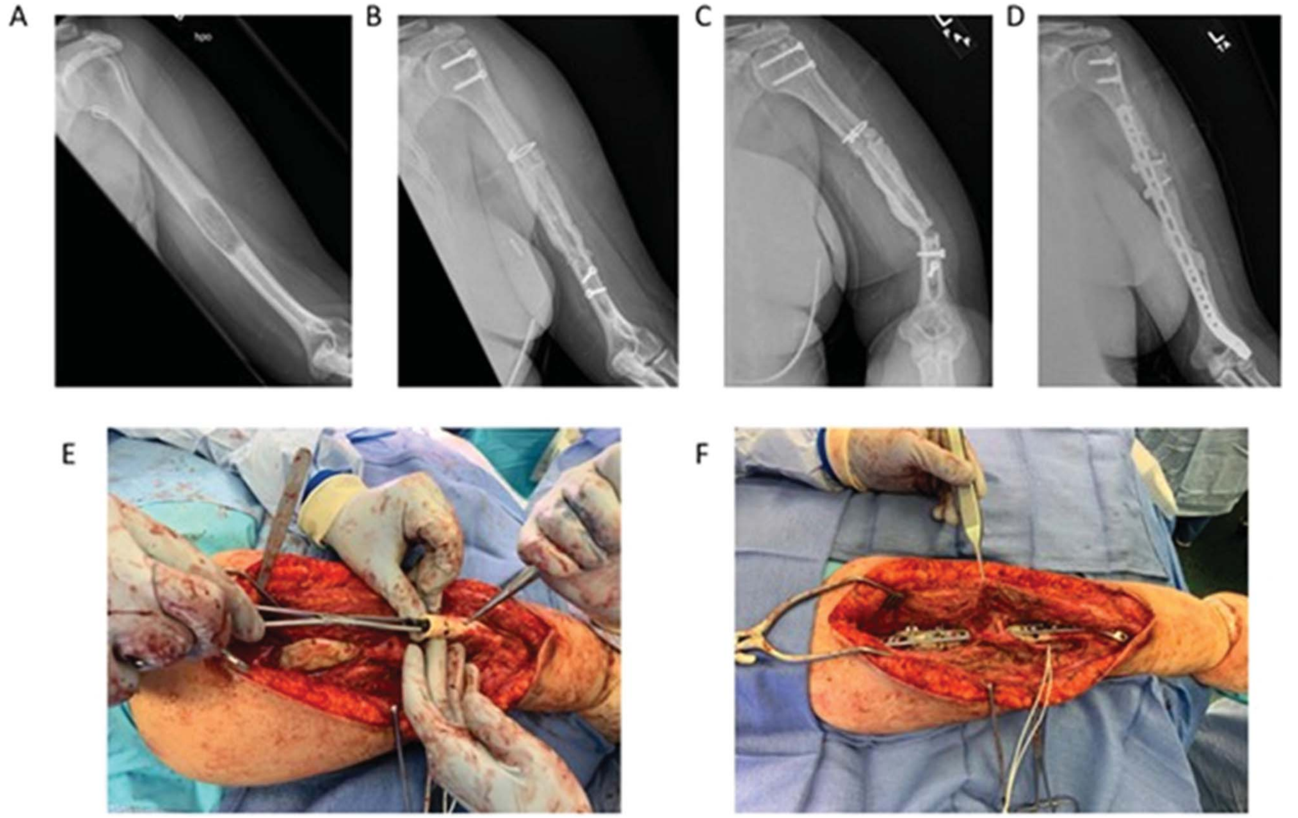
Radiographs showing a 83-year-old male patient with metastatic renal cell carcinoma and impending pathological fracture of the left femur because of visceral load of disease and brain metastasis who received a carbon-fiber nail for prophylactic stabilization (**A**). Despite systemic treatment, there was notable disease progression (**B**) with ultimate implant fracture (**C**). The patient required revision to proximal femur replacement (**D**).

because of concerns for infection and need to complete systemic therapy. This failure was at the interface between the bone and cement spacer, suggesting that the failure was secondary to a modulus of elasticity mismatch (Figure 5). Nonmechanical failures occurred in 22 patients (9.2%), including 8 (3.3%) peri-implant infections requiring surgical treatment and 15 (6.3%) tumor progressions with implant contamination. One patient required intraoperative removal of the CF nail as the metal thread of the head screw disassembled from its CF body. There is no tool to remove this metal thread as all instruments attach to the CF core of the screw. After several attempts with pliers, the metal thread could not be removed from the femoral neck/head. The patient received a proximal femoral replacement because a new nail could not be inserted (Figure 6). Two patients required amputations. One of them is a patient with thigh pleomorphic sarcoma with recurrence who sustained a peri-implant femoral fracture without nail structural failure. The second amputation was for the management of a failed free flap in a patient with oligometastatic bone disease secondary to uterine cancer affecting the tibia. Two incidences of noninfectious wound dehiscence occurred (Table 3). Subgroup analyses between prophylactic stabilization of impending and fixation of complete pathological fractures showed similar failure results. No other subgroup analyses were performed because of limited numbers in each group.

Implant Failure Risk Factors

Preoperative radiation therapy at the surgical site and femur surgery were associated with increased complication risk in all groups after adjusting for confounders during the analysis (overall complications without time constraint: OR, 4.35; 95% CI: 1.85 to 10.25; $P = 0.001$ and OR, 3.15; 95% CI:1.24 to 8.05; $P = 0.02$, respectively; Supplementary Table III, http://links.lww.com/JAAOS/A955). Additional bone metastases to the surgical site were associated with an increased risk of implant failures in overall complications without time constraints and without tumor progression within 1 year, but not in the other two groupings. The primary tumor group with good prognosis appeared to be associated with an increased risk of implant failures when no time constraint was applied. However, that association disappeared when we investigated only the events within 1 year. The follow-up time and 1-year survival for patients with a good tumor prognosis were

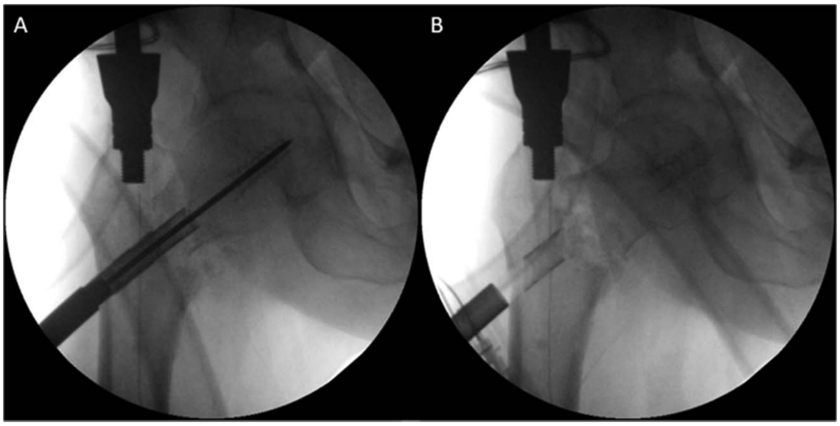
Figure 5



Radiographs showing a 38-year-old female patient with oligometastatic disease secondary to synovial sarcoma. Preoperative radiograph demonstrating an isolated intramedullary left humeral lesion (**A**). Six months after intercalary reconstruction with cemented spacer and carbon-fiber nail because of concern of infection (**B**). Complete failure of implant at host bone-cement interface (**C**). Revision surgery with plate augmentation and fixation after removal of the distal portion of nail (**D**). Intraoperative removal of distal portion of broken nail (**E**) and after revision surgery with metal plate augmentation (**F**).

considerably longer and better than those with poor tumor prognosis (median follow-up time: 333 (IQR, 91 to 693) days versus 93 (IQR, 28 to 239) days; 1-year survival: 64% versus 23%). The competing risk of death may explain why patients with "good prognosis" tumors had more failures as they had more time to develop them than patients with poor prognoses who died earlier and had shorter follow-up times.

Figure 6



Images showing insertion of screw under fluoroscopy (**A**) and disassembly from guidewire (**B**).

Discussion

Intramedullary nails are part of the traditional treatment armamentarium for metastatic disease in the long bones (impending or complete pathological fractures). Although fixation with traditional titanium implants reports satisfactory clinical and functional outcomes, oncology patients are more critically affected by their drawbacks. Some of the limitations include metal scattering on MRI and/or CT, lack of similarity to bone elastic moduli, and scattering effect in radiation therapy planning.[13,18,27] The radiolucency of CF theoretically facilitates surveillance and radiation therapy planning using MRI or CT scans, respectively.[27] Especially in the subset of patients treated with surgical curative intent, that is, the localized sarcoma group, who undergo regular MRI surveillance for recurrence. Despite the absent literature about early detection of recurrence or tumor progression on CT or MRI in long bones, there are some reports highlighting the benefit in planning of radiation therapy, at least in cadaver studies.[16,28,29] Finally, more reflective bone elastic moduli in CF implants may decrease host bone/implant mismatch when compared with their titanium counterparts. In theory, this may reduce mid-thigh pain reported by patients treated with titanium femoral nails suffering from host bone/implant modulus mismatch. CF implants also maintain higher ex vivo biomechanical profiles, potentially reducing implant structural complications secondary to fracture nonhealing or disease progression modeled by loading with axial or lateral bending forces.[10] However, previous studies reported mixed results regarding the fatigue strength and durability of CF implants.[16,17,21] Although CF nails may have reduced risks of fatigue failure, some nails still failed.

Compared with historic data, complication rates seem comparable for mechanical implant failures between CF and titanium implants, although the titanium rates variated and had nonuniform definitions in the literature.[2,3,30] Acquiring more data is of utmost importance to provide insights into failure mechanisms. Our international multicenter database is designed to include patients treated with CF implants continuously and could facilitate data for future studies to identify risk factors for nail failures. Altogether, these insights could lead to ideas on improving implant material and/or usage in a specific subset of patients to optimize patient care. Although CF implants report comparable rates of wound dehiscence and superficial infections, thromboembolic events, failure because of disease progression, and rates of adverse events, their unique radiographic and biomechanical properties encourage further research.[17,23,30-35] For example, a more effective and controlled delivery of radiation therapy because of lack of scattering effect may translate in lower soft-tissue and wound complications. Still, previous studies report mixed results with relatively high nonunion rates in a single center using 16 CF nails for diaphyseal correction osteotomy (11 limbs), shortening surgery (3 limbs), and diaphyseal closed tibial fractures (2 limbs), and low nonunion rates in a multicenter study with 96 oncologic patients treated with CF plates.[21,22] Besides, a single-institutional study in 2017 investigated 53 CF nails in oncologic patients of which one nail developed a stress fracture proximally to the distal static screw, and a more recent single-institutional case-control study (with 36 titanium nails and 36 CF nails) demonstrated no differences between both groups regarding operating time, surgical wound infection, and survival.[35,36] Our findings, together with the above studies, highlight an acceptable mechanical failure rate in the oncologic population, which has also been reported for titanium nails (Supplementary Table II, http://links.lww.com/JAAOS/A954). Failure predictors are similar for both and depend on patients' disease progression, the burden of metastatic disease, and tumor location.[2,3] The time-constrained analysis seems to have no effect on the nature, incidence, and rate of complications.

Complications were found to be associated with nail type. Humeral and femoral nails had structural failures while tibial nails did not. Humeral nails fixing distal humeral diaphyseal segmental defects were more likely to break. In the one case in which a cement spacer was used, the stress caused by the difference in elastic moduli between the cement spacer filling the diaphyseal defect and the distal humerus fragment apparently generated point forces in the distal third of the nail, causing the fracture of the implant at that level. For the remaining ones, the mismatch apparently was between the distal diaphysis and distal metaphysis. Theoretically, such fractures may be prevented by increasing humeral nail diameter or by opting for intercalary allografts instead of cement spacers. Alternatively, metal plate constructs and traditional megaprostheses might be used instead with their own benefits and complications. For femoral nails, failure occurred with impending and complete pathologic fractures where neoplastic tissue was not removed or only curetted. Fractures occurred at the proximal metadiaphyseal junction or the diaphyseal portion of the nail. It is important to highlight that at least one of the failures was due to disease progression, and the nail was left in place until it failed because of plans of not stopping

Table 4. Patient Characteristics for Structural Failures (n = 7)

Sex	Age	American Society of Anesthesiologists	Bone	Primary Tumor	Location	Type of Fracture	Resection	Postoperative day
Female	54	2	Femur	Lung	Metadiaphyseal	Impending	Intralesional	186
Male	65	3	Femur	Multiple myeloma	Diaphyseal	Fracture	No resection	654
Male	78	3	Femur	Kidney	Diaphyseal	Fracture	No resection	84
Male	77	3	Femur	Other	Metadiaphyseal	Impending	Intralesional	18
Female	64	2	Femur	Other	Metadiaphyseal	Fracture	Intralesional	69
Male	57	3	Humerus	Kidney	Diaphyseal	Fracture	Marginal	214
Male	71	3	Humerus	Kidney	Diaphyseal	Fracture	Intralesional	34

systemic treatment (Figure 4). All patients underwent revision surgery without complications. Table 4 summarizes implant structural failures.

The study is limited by its retrospective design, lack of patient matching, and potential heterogeneity in institutional patient data collection. This study should be interpreted in the context of its retrospective design and inherent shortcomings. However, the effect of the retrospective nature was deemed minimal as the survival and failure outcomes are incontrovertible. There was no direct comparison with patients who received non-CF nails at the participating institutions. Ideally, an randomized controlled trial (RCT) or propensity score–matched study may be a better option. However, this would have been difficult given the relatively small population of patients with long bone metastases and the large size of this multicenter cohort, the biggest of its kind to our knowledge. This design should serve as the platform for a future prospective study randomizing patients to each nail type. This study also depended on each participating center to fill in its own data. Although we believe each institution filled in their data to the prospective registry to the best of their ability, following clearly defined criteria and extraction sheets, inconsistencies may still be present. If additional relevant information was required, the primary surgeon was contacted to clarify any discrepancies discovered during patient record review to minimize selection and recall bias. Finally, the sample size prevented us from performing subgroup analyses to detect any differences between, for example, soft-tissue sarcoma and metastatic carcinoma. Nevertheless, to our knowledge, this is the largest CF implant cohort determining complication profiles in patients treated surgically with CF nails for impending or completed pathologic fractures. By our international, multicenter effort, our study provides valuable insights into the use of CF nails in orthopaedics oncology care.

Conclusion

CF implants might be an alternative treatment option for impending and complete pathological fractures secondary to bone metastases. Their complications and failure rates seem to be comparable with those historically reported in titanium and stainless-steel implants. Given their radiolucency, higher biocompatibility, bone-like elastic moduli, lack of scattering effect on MRI and CT, and strength on axial loading and bending forces, CF may particularly benefit oncology patient populations requiring frequent imaging follow-ups with MRI and/or CT scans and careful planning for postoperative radiation therapy treatment plans. Additional studies of randomized, comparative nature are needed to confirm the similar complication profiles for these implants. Relevant future research studies comparing the prospective benefits of early detection on imaging studies of local recurrence and/or tumor progression, as well as optimization of radiation therapy planning will help affirm the future standard of care for pathological fracture management in orthopaedic oncology patients. Owing to the rarity of these events, international, multi-institutional collaborations are required to facilitate these studies.

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